

DISCOVERY OF A FLAT-SPECTRUM RADIO NUCLEUS IN NGC 3115

J. M. WROBEL^{1,2} AND K. NYLAND³

9/27/12 for AJ

ABSTRACT

The early-type galaxy NGC 3115, at a distance of 10.2 Mpc, hosts the nearest billion-solar-mass black hole. Wong et al. recently inferred a substantial Bondi accretion rate near the black hole. Bondi-like accretion is thought to fuel outflows, which can be traced through their radio emission. This paper reports the discovery of a radio nucleus in NGC 3115, with a diameter less than $0.17''$ (8.4 pc), a luminosity at 8.5 GHz of 3.1×10^{35} ergs s⁻¹ and a flat spectrum ($\alpha = -0.23 \pm 0.20$, $S \propto \nu^\alpha$). The radio source coincides with the galaxy's photocenter and candidate X-ray nucleus. The emission is radio-loud, suggesting the presence of an outflow on scales less than 10 pc. On such scales, the Bondi accretion could be impeded by heating due to disruption of the outflow.

Subject headings: galaxies: active — galaxies: individual (NGC 3115) — galaxies: nuclei — radio continuum: galaxies — X-rays: galaxies

1. MOTIVATION

Studies of the nearest massive black holes (MBHs) offer unique insights into inflows and outflows in galactic nuclei. Such MBHs can be investigated on a key, physically-defining scale. Spherically symmetric, adiabatic accretion is characterized by a Bondi radius $R_B = 2GM_\bullet/c_s^2$ and accretion rate $\dot{M}_B = \pi R_B^2 \rho c_s$, where M_\bullet is the MBH mass, and ρ and c_s are the density and sound speed of the thermal gas at R_B . For the nearest galaxies $R_B \sim 100$ pc, which can be spatially resolved by *Chandra* and allows \dot{M}_B to be inferred (e.g., Pellegrini 2005).

Jet-like outflows are a hallmark of low-luminosity active galactic nuclei (AGNs) (Nagar et al. 2005; Ho 2008, and references therein) and are thought to be fueled by Bondi-like inflows (e.g., Pellegrini 2005). On scales of order R_B or more, such outflows can be traced by radio imaging of jets and lobes, and X-ray imaging of jet-induced cavities in the thermal gas (e.g., Allen et al. 2006; McNamara & Nulsen 2007). On scales much less than R_B , such outflows have only been traced using radio imaging (Nagar et al. 2005, and references therein).

This work focuses on the nearest billion-solar-mass BH, that hosted by the flattened early-type galaxy NGC 3115 (Kormendy et al. 1996; Emsellem et al. 1999). A distance of $D = 10.2$ Mpc, a nominal BH mass of $M_\bullet = 9.6 \times 10^8 M_\odot$ and a 1σ mass range of $M_\bullet = 6.7 - 15 \times 10^8 M_\odot$ (Emsellem et al. 1999; Gültekin et al. 2009a) are adopted. For a canonical radiative efficiency of $\eta = 0.1$, the associated Eddington luminosity is a quasar-like $L_{\text{Edd}} = 1.2 \times 10^{47}$ ergs s⁻¹. The MBH is embedded in a nuclear star cluster located at the photocenter of NGC 3115's stellar disk and cuspy bulge (Kormendy et al. 1996; Emsellem et al. 1999; Lauer et al. 2005). Table 1 gives the position of the galaxy photocenter.

NGC 3115 is hot-gas poor and its overall gas temperature, 0.4 keV, is atypically high compared to early-type galaxies with similar hot-gas contents (Boroson et al. 2011). Wong et al. (2011) report that the gas temperature is 0.3 keV in a $4'' - 10''$ annulus and begins to rise at a radius of $4'' - 5''$. This was interpreted as evidence for spatially resolving the Bondi flow onto the MBH, with the flow characterized by $R_B = 4'' - 5''$ (200-250 pc) and $\dot{M}_B = 2.2 \times 10^{-2} M_\odot \text{ yr}^{-1}$. This Bondi radius is consistent with expectations given the uncertainty in the BH mass (Gültekin et al. 2009a).

A basic tenet of Bondi accretion theory is that the flow is adiabatic, a situation that could be violated if heating mechanisms are in play near the MBH. Here, we set the stage for examining the role of outflows that could potentially heat the flow toward the MBH in NGC 3115. We present new radio constraints on any outflows (§ 2) and interpret those constraints within the context of other information on NGC 3115 (§ 3). We close in § 4 with a summary and conclusions.

2. IMAGING

NGC 3115 was observed with the Very Large Array (VLA; Thompson et al. 1980) in its A configuration on 2004 November 16 UT under proposal code AT299. A coordinate equinox of 2000 was employed. J1007-027, at a position of $\alpha(J2000) = 10^h 07^m 04^s.3499$, $\delta(J2000) = -02^\circ 07' 10''.917$ and with a one-dimensional position error at 1σ better than 1 mas, was used as a phase calibrator. The switching time between it and NGC 3115 was 490 s, with a switching angle of 5.6° . To avoid phase-center artifacts, the *a priori* pointing position for NGC 3115 was about $0.2''$ South of the then-available *Chandra* position. Data were acquired in dual circular polarizations with a bandwidth of 0.1 GHz centered at 8.4601 GHz (8.5 GHz hereafter). Observations of 3C 286 were used to set the amplitude scale to an accuracy of about 3%. The net exposure time on NGC 3115 was 5180 s.

The data were calibrated and imaged using release 3.3.0 of the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007). Twenty-five of 27 antennas provided data of acceptable quality, with most of the data loss due to EVLA (Perley et al. 2011)

¹ National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; jwrobel@nrao.edu

² The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

³ New Mexico Tech, Department of Physics, 801 Leroy Place, Socorro, NM 87801; knyland@nrao.edu

retrofitting activities. The CASA task `clean` was used to form and deconvolve a naturally-weighted image of the Stokes I emission from NGC 3115. NRAO's Astronomical Image Processing System (AIPS) (Greisen 2003) was used for image analysis. Figure 1 shows the image, which has an rms noise level of $\sigma = 0.018$ mJy beam $^{-1}$. A search within the NED/2MASS error circle (Table 1) led to the detection of one source. A Gaussian fit to that source in the image plane was made using the AIPS task `JMFIT`. From this fit, the source was found to be compact with a diameter less than $0.17''$ and with an integrated flux density of $S_{8.5 \text{ GHz}} = 0.29 \pm 0.03$ mJy, where the quoted error is the quadratic sum of the 3% scale error and the error in the fit. The fit also yielded a position at 8.5 GHz with an error dominated by that due to the phase-referencing strategies (Table 1, Fig. 1). With adequate signal-to-noise, structures as large as $6''$ could be represented in Figure 1. No extended structure was found.

A VLA image of NGC 3115 at 1.4 GHz is also available from the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey of White et al. (1997). Near the 8.5 GHz position there is a weak detection at 1.4 GHz obtained on 2002 August 12 UT with a geometric resolution of $5.9''$. Because of the source's weakness, a parabolic fit in the image plane was made using the AIPS verb `MAXFIT`. This fit yielded a peak flux density of $S_{1.4 \text{ GHz}} = 0.44 \pm 0.15$ mJy beam $^{-1}$, only 2.9 times the local rms noise level. The fit also provided a position at 1.4 GHz with an error dominated by that due to the signal-to-noise ratio (Table 1, Fig. 1). NGC 3115 was also observed briefly at 1.4 GHz under proposal code AT299; those data were calibrated and imaged but that image is not presented here because it had poorer sensitivity than the FIRST image.

3. IMPLICATIONS

3.1. The Radio Nucleus

From Figure 1, the 8.5 GHz detection of NGC 3115 has a diameter less than $0.17''$ (8.4 pc). Its flux density is consistent with the 3σ upper limit of 0.33 mJy measured at 4.9 GHz by Fabbiano et al. (1989) with a geometric resolution of $8.5''$ (420 pc), and thus on the Bondi-zone scales (Wong et al. 2011) shown in Figure 1. Such photometric consistency implies that Figure 1 is recovering almost all of the high-frequency emission within the Bondi zone. The photometry being compared at 4.9 and 8.5 GHz is separated by 17 years. If this comparison is compromised by time variability, the case for the compact nature of the high-frequency emission would be strengthened. The available high-frequency data provide no evidence for extended radio emission within the Bondi zone. In this circumstance the spectral index between 8.5 and 1.4 GHz can be usefully computed: it is $\alpha = -0.23 \pm 0.20$ ($S \propto \nu^\alpha$). This index could be compromised by time variability over about two years but, again, such variability would strengthen the case for the compact nature of the radio emission.

The compact, flat-spectrum radio source coincides astrometrically with NGC 3115's photocenter (Table 1, Fig. 1). Because of this astrometric agreement, Table 1 refers to this source as the radio nucleus of NGC 3115. Its luminosity is $\nu L_\nu(8.5 \text{ GHz}) = 3.1 \times 10^{35}$ ergs s $^{-1}$.

3.2. The Candidate X-ray Nucleus

Zhang et al. (2009) identified a pointlike *Chandra* source close to the galaxy's photocenter (and thus its MBH) and surrounded by diffuse X-ray emission. Other studies also suggest a pointlike X-ray source (Ho 2009; Gültekin et al. 2009b; Boroson et al. 2011; Miller et al. 2012). After correction for stellar and thermal emission, Boroson et al. (2011) find that the pointlike source has a hard spectrum, a 2-10 keV luminosity of $L_X = 4.3 \times 10^{38}$ ergs s $^{-1}$ and an Eddington fraction of $L_X/L_{\text{Edd}} = 3.6 \times 10^{-9}$. Table 1 gives the position of this nuclear X-ray source, CXO J100513.9-074307, from Release 1.1 of the *Chandra* Source Catalog (Evans et al. 2010). However, both Wong et al. (2011) and Miller et al. (2012) note possible blending issues that could affect both the astrometry and photometry of this source. For this reason, the cited X-ray luminosity and Eddington fraction are conservatively treated as upper limits ($L_X < 4.3 \times 10^{38}$ ergs s $^{-1}$, $L_X/L_{\text{Edd}} < 3.6 \times 10^{-9}$) and Table 1 refers to this source as the candidate X-ray nucleus of NGC 3115.

3.3. Potentially Heating the Inflow

The compact, flat-spectrum radio source coincides astrometrically with NGC 3115's candidate X-ray nucleus (Table 1, Fig. 1). A study of radio and X-ray sources in low-luminosity AGNs found that the majority are radio loud, defined as $\log R_X = \log \nu L_\nu(5 \text{ GHz})/L_X = -4.5$ or higher (Terashima & Wilson 2003). That study involved radio sources with flat or inverted spectra, so the cited definition applies equally well at 8.5 GHz as at 5 GHz. For NGC 3115, $\log R_X = \log \nu L_\nu(8.5 \text{ GHz})/L_X > -3$, implying it is radio-loud. As conservatively estimated above, the Eddington fraction of the MBH in NGC 3115 is $L_X/L_{\text{Edd}} < 3.6 \times 10^{-9}$. This is remarkably small given that Wong et al. (2011) find that the Bondi inflow onto the MBH is characterized by a substantial accretion rate of $\dot{M}_B = 2.2 \times 10^{-2} M_\odot$ yr $^{-1}$ at a radius of $R_B = 4'' - 5''$ (200-250 pc). Could this inflow be somehow impeded, limiting the fuel supplied to the MBH? Indeed, the density slope inferred by Wong et al. (2011) led them to suggest that the accretion was being suppressed near the MBH.

The compact, flat-spectrum and radio-loud nature of many low-luminosity AGNs has been demonstrated to arise from outflows on parsec scales (Nagar et al. 2005; Ho 2008, and references therein). The radio nucleus of NGC 3115 is compact, has a flat spectrum and is radio-loud, so it could plausibly support an outflow on parsec scales. Mechanical feedback from such an outflow could heat, and thus impede, the Bondi inflow characterized by Wong et al. (2011). To be most effective, the parsec-scale outflow should be poorly collimated, curved and/or bent, traits often seen among low-luminosity AGNs (Nagar et al. 2005). For example, the iconic low-luminosity AGN in the early-type galaxy NGC 4278 has long been known to feature flat-spectrum and radio-loud emission on parsec scales (Giroletti et al. 2005, and references therein). Notably, Pellegrini et al. (2012) recently concluded that the distorted, parsec-scale jets in NGC 4278 play a key role in heating the ambient medium in this early-type galaxy. Our discovery of compact, flat-spectrum and radio-loud emission from NGC 3115 sets

the stage for future radio imaging using very long baseline interferometry (VLBI). Knowing the radio structure of NGC 3115 on parsec scales, its potential for heating the ambient medium can be quantified.

It is also possible that the inflow is heated by stellar motions in NGC 3115's parsec-scale nuclear cluster, for which the innermost velocity dispersion reaches about 600 km s^{-1} (Kormendy et al. 1996). Hillel & Soker (2012) recently presented a theoretical study of this effect. Such stellar-based heating could also influence the formation and propagation of outflows driven by the MBH in NGC 3115. For example, if it is difficult for the outflow to propagate then VLBI imaging could show emission confined to sub-parsec scales.

3.4. Radio Emission from an Outflow or Inflow?

A word of caution is in order. The flat-spectrum radio source in NGC 3115 has an 8.5 GHz luminosity that is only about 290 times that of the flat-spectrum source Sagittarius A*, the radio nucleus of the Milky Way (Genzel et al. 2010, and references therein). That nucleus is about eight orders of magnitude underluminous compared to its Eddington luminosity. There is an ongoing debate about whether the steady radio emission from Sagittarius A* traces an outflow, arises from the accretion flow itself, or involves both phenomena (Yuan 2011, and references therein). Thus, at these low radio luminosities, outflows could be entirely absent and unavailable for heating. Structural information on parsec scales could help distinguish between these two scenarios for NGC 3115, further underscoring the need for VLBI imaging. Such imaging could reveal either elongated structures that are outflow driven or pointlike emission from the accretion flow near the MBH. In the interim, the radio photometry presented here can help constrain models of the emission from the outflows and/or inflows in the vicinity of the billion-solar-mass BH in NGC 3115.

4. SUMMARY AND CONCLUSIONS

We analyzed archival 8.5 GHz VLA observations from the A-configuration of the nucleus of NGC 3115 and de-

tected, for the first time, compact emission (diameter $< 8.4 \text{ pc}$) with a luminosity of $3.1 \times 10^{35} \text{ ergs s}^{-1}$. The compact radio emission in NGC 3115 is spatially coincident with the optical center of the galaxy as well as the candidate X-ray nucleus. In addition to the 8.5 GHz detection, we found a weak detection in the FIRST image at 1.4 GHz and showed that the emission has a flat radio spectrum, with a spectral index of $\alpha = -0.23 \pm 0.20$. We compared the 8.5 GHz and 2-10 keV luminosities and found that NGC 3115 is radio-loud, with $\log R_X > -3$.

Wong et al. (2011) recently reported a *Chandra* detection of a centrally-rising gas temperature gradient in the nucleus of NGC 3115, and cited this detection as evidence of spatially resolved Bondi accretion onto the MBH on scales of 200-250 pc with $\dot{M}_B = 2.2 \times 10^{-2} M_\odot \text{ yr}^{-1}$. However, this substantial Bondi accretion rate is at odds with the extremely low Eddington fraction of $L_X/L_{\text{Edd}} < 3.6 \times 10^{-9}$, suggesting that heating within the nucleus of NGC 3115 may be impeding the Bondi inflow. As has been established in other low-luminosity AGNs, the radio-loud nature of NGC 3115 could be the result of a parsec-scale outflow capable of heating the ambient gas and starving the central MBH. The high-velocity stellar motions in the parsec-scale nuclear star cluster in NGC 3115 also have the potential to heat the central gas, possibly hindering the accretion of material onto the MBH and confining any outflows to sub-parsec scales. Alternatively, pointlike radio emission could also arise from the accretion flow itself. Future, sensitive VLBI observations are needed to distinguish among these possibilities.

This research has made use of data obtained from the *Chandra* Source Catalog, provided by the *Chandra* X-ray Center (CXC) as part of the *Chandra* Data Archive. We are grateful to Yuichi Terashima, Luis Ho and Jim Ulvestad for their early efforts in proposing and observing AT299.

Facilities: *Chandra*, VLA.

REFERENCES

- Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, *MNRAS*, 372, 21
- Boroson, B., Kim, D.-W., & Fabbiano, G. 2011, *ApJ*, 729, 12
- Emsellem, E., Dejonghe, H., & Bacon, R. 1999, *MNRAS*, 303, 495
- Evans, I. N. et al. 2010, *ApJS*, 189, 37
- Fabbiano, G., Gioia, I. M., & Trinchieri, G. 1989, *ApJ*, 347, 127
- Genzel, R., Eisenhauer, F., & Gillessen, S., *Rev. Mod. Phys.*, 82, 3121
- Giroletti, M., Taylor, G. B., & Giovannini, G. 2005, *ApJ*, 622, 178
- Greisen, E. W. 2003, in *Information Handling in Astronomy*, ed. A. Heck (Dordrecht: Kluwer), 109
- Gültekin, K., et al. 2009a, *ApJ*, 698, 198
- Gültekin, K., Cackett, E. M., Miller, J. M., Di Matteo, T., Markoff, S., & Richstone, D. O. 2009b, *ApJ*, 706, 404
- Hillel, S., & Soker, N. 2012, *Galaxy Clusters as Giant Cosmic Laboratories*, (Madrid, Spain: ESA), 22
- Ho, L. C. 2008, *ARA&A*, 46, 475
- Ho, L. C. 2009, *ApJ*, 699, 626
- Kormendy, J. et al. 1996, *ApJ*, 459, L57
- Lauer, T. R., et al. 2005, *AJ*, 129, 2138
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, *Astronomical Data Analysis Software and Systems XVI* (ASP Conf. Ser. 376), ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
- McNamara, B. R., & Nulsen, P. E. J. 2007, *ARA&A*, 45, 117
- Miller, B., Gallo, E., Treu, T., & Woo, J.-H. 2012, *ApJ*, 747, 57
- Nagar, N. M., Falcke, H., & Wilson, A. S. 2005, *A&A*, 435, 521
- Pellegrini, S. 2005, *ApJ*, 624, 155
- Pellegrini, S., et al. 2012, *arXiv:1206.2533v1*
- Perley, R. A., Chandler, C. J., Butler, B. J., & Wrobel, J. M. 2011, *ApJ*, 739, L1
- Terashima, Y., & Wilson, A. S. 2003, *ApJ*, 583, 145
- Thompson, A. R., Clark, B. G., Wade, C. M., Napier, P. J., 1980, *ApJS*, 44, 151
- White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, *ApJ*, 475, 479
- Wong, K.-W., Irwin, J. A., Yukita, M., Million, E. T., Mathews, W. M., & Bregman, J. N. 2011, *ApJ*, 736, L23
- Yuan, F. 2011, *The Galactic Center: A Window to the Nuclear Environment of Disk Galaxies* (ASP Conf. Ser. 439), ed. M. R. Morris, Q. D. Wang, & F. Yuan (San Francisco, CA: ASP), 346
- Zhang, W. M., Soria, R., Zhang, S. N., Swartz, D. A., & Liu, J. F. 2009, *ApJ*, 699, 281

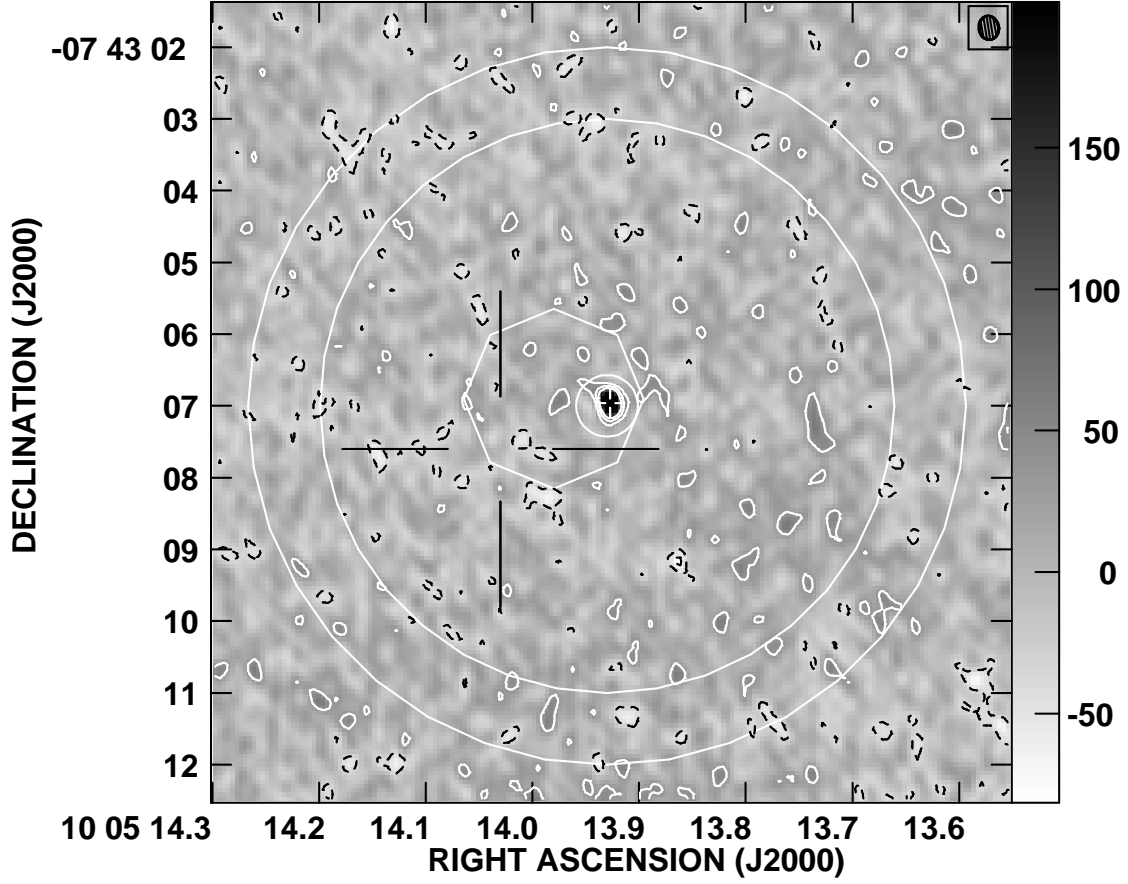


FIG. 1.— VLA image of Stokes I emission from NGC 3115 at a frequency of 8.5 GHz and spanning $11''$ (540 pc). The symbols mark positions and their errors at the 95% confidence level (Table 1). Symbols are an octagon for the NED/2MASS position, a small circle for the candidate X-ray nucleus, a large cross with a gap for the 1.4 GHz nucleus; and a small cross with a gap for the 8.5 GHz nucleus. In addition, the large circles encode the range in the Bondi radius from Wong et al. (2011). For the 8.5 GHz image, natural weighting was used, giving an rms noise of $0.018 \text{ mJy beam}^{-1}$ (1σ) and beam dimensions at FWHM of $0.33'' \times 0.27''$ with elongation PA = 9° (hatched ellipse). Allowed contours are at $-6, -4, -2, 2, 4$, and 6 times 1σ . Negative contours are dashed and positive ones are solid. Linear grey scale spans $-0.08 \text{ mJy beam}^{-1}$ to $0.20 \text{ mJy beam}^{-1}$. Scale is $1'' = 49.5 \text{ pc}$

TABLE 1
ASTROMETRY OF NUCLEAR COMPONENTS

Component (1)	R.A. (J2000) (2)	Decl. (J2000) (3)	Error ($''$) (4)	Ref. (5)
$2 \mu\text{m}$ galaxy photocenter	10 05 13.98	-07 43 06.9	1.25	1
Radio nucleus, 8.5 GHz	10 05 13.927	-07 43 06.96	0.20	2
Radio nucleus, 1.4 GHz	10 05 14.03	-07 43 07.6	2.2	2
Candidate X-ray nucleus	10 05 13.93	-07 43 07.0	0.43	3

REFERENCES. — (1) NED/2MASS; (2) this work; (3) Evans et al. 2010, Release 1.1.

NOTE. — Col. (1): Component. Cols. (2) and (3): Component position. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (4): Diameter of error circle at 95% confidence level. Col. (5): Reference.